DESIGN CONSIDERATIONS AND IMPLEMENTATION OF VERY-LARGE SCALE MANUFACTURING OF CIGS SOLAR CELLS AND RELATED PRODUCTS

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ABSTRACT: Discrete CIGS solar cells on flexible metal substrates offer an alternative to wafer-Si based cells. The manufacture of this cell technology additionally offers capital cost, throughput and yield advantages over the manufacture of either wafer-Si or traditional monolithically integrated thin-film modules. Economies of scale and volume can be achieved with the implementation of gigawatt-scale manufacturing. Likewise, vertical integration within the production line to include In refinement, steel substrate finishing, source material synthesis and formation, as well as module packaging materials (either glass and Al or plastic) provide for optimization of cost and supply-chain issues.

Keywords: CIGS, Photovoltaic, Solar City, Solar Cell, Solar Panel, Learning Curve

1. INTRODUCTION

Electricity demand is predicted to grow at an annual rate of 2.3 - 3.4% in the coming decade, depending on assumptions made [1]. In one scenario, where every planetary citizen is provided access to 2 kW of electricity supply by the middle of the century (the U.S.A. is at 3 kW per capita), the peak demand for electrical power increases from 4 terawatt (1TW = 10^{12} W) to 18.4 TW (Table I). It is both unlikely and undesirable that the increase in demand will be fulfilled by traditional hydrocarbon energy resources.

Table I: Electrical demand estimates

	World Pop.	Per Capita Demand	Peak Demand[a]	Peak Demand[b]
2004	6.38 B	0.6 kW	4.0 TW	4.0 TW
2050	9.22 B	2.0 kW	11.4 TW	18.4 TW

[a] 2050 demand from pop. growth & per capita demand
[b] 2050 demand from IEA growth rate of 2.3%

Clean energy resources, such as wind and solar, have the opportunity to backfill the demand. Of all non-carbon based resources, solar is believed to be the only energy resource that can ubiquitously meet the "Terawatt Challenge" [2]. With a current annual global production capacity of approximately one gigawatt (1GW = 10^9 W), the photovoltaics (PV) industry requires substantial growth in order to effectively meet the challenge. Additionally, the cost of components throughout the PV system product chain must be significantly reduced to achieve improved cost-competitiveness.

Keshner and Arya [3] recently examined this issue and came to three primary conclusions:

1. $1.00 /watt at the system level is required to achieve cost-competitiveness with traditional power generation choices.
2. The $1.00/watt benchmark cannot be achieved with crystalline Si solar cell technologies.
3. Multi-GW factories producing thin-film PV modules is the enabling factor in achieving the $1.00/W cost benchmark.

This paper examines a specific roadmap for the achievement of 2.0 GW/yr production of Cu(In,Ga)Se$_2$ ("CIGS") solar cells and modules. In contrast to the aforementioned study, we consider the following:

1. The production of CIGS solar cells by a continuous in-line process at higher unit volumes (200 MW / machine) offers capital investment advantages relative to the manufacture of traditional monolithically integrated panels.
2. Flexible solar cells offer opportunities for non-rigid packaging that can lower implementation costs in the field. On-site Glass and aluminum sub-factories, considered a requirement to lower module costs, can be replaced with polymer, polymer composite, and steel finishing factories.
3. Control of the raw material supply chain, especially In, Ga and Se, and their synthesis and formation into source materials, such as sputtering targets, will be an important component in realizing full cost reductions.
4. Higher profit margins in the near-term resulting from system sales prices of $1-$3/W offer accelerated return-on-investment opportunities to justify the up-front capital investment required to achieve multi-GW scale manufacturing in multiple locations.

2 CIGS SOLAR CELLS AND MANUFACTURING

2.1 CIGS Solar Cell Technology

Solar cells based upon the CIGS p-type absorber have been under development for over 25 years. CIGS has proven to be both highly efficient, with laboratory performance approaching 20% [4], and highly reliable in the field, with lifetimes exceeding 18 years with little or no degradation. Unfortunately, there has not been substantial market penetration by this technology, in part
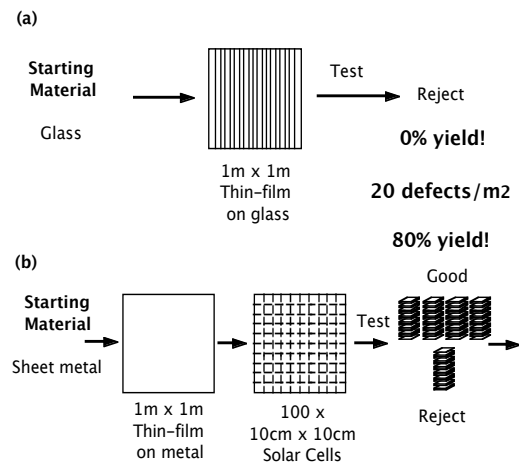
Figure 1: Illustration of (a) dis-economy of yield associated with monolithic integration of thin-film PV in contrast to (b) production of discrete solar cells.

due to the dis-economies of scale associated with the production of monolithically integrated modules (Fig. 1a). Unlike flat-panel displays in its early days, where there existed substantial markets for smaller devices and/or markets that were willing to pay the premium associated with low yields, CIGS and other thin-film PV, especially if fabricated in rigid form-factors, typically must sell at market commodity prices established by wafer-Si modules.

DayStar is a pioneer in the fabrication of discrete CIGS solar cells on flexible metal substrates (Fig. 2). Since CIGS has very similar electrical properties as crystalline Si, there exists the opportunity for CIGS cells to substitute for and/or displace wafer-Si cells in the marketplace. Additionally, fabricating discrete solar cells that are extracted from larger metal sheets or rolls (Fig. 1b) offers opportunities for attractive yields prior to production maturity.
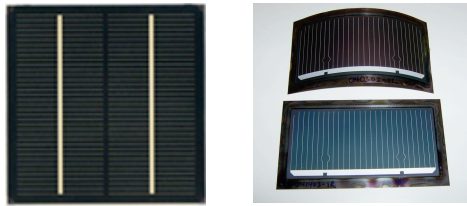
Figure 2: Photograph of 100mm x 100mm (l) and 40mm x 80mm CIGS cells on metal substrates.

2.2 CIGS Solar Cell Manufacturing

The production of discrete CIGS solar cells also offers the opportunity for continuous manufacture of the high-value solar cell stack without the need for a vacuum break to accomplish scribing steps. Additionally, DayStar has chosen a manufacturing methodology that will enable very high throughput through the production hardware. Once the semiconductor stack has been deposited, the cell may be finished in an automated fashion by a sequence of steps that includes the printing of grids, cell isolation/cutting and performance binning.

3 GIGAWATT-SCALE MANUFACTURING

The scale-up of CIGS solar cell and module manufacturing to gigawatt-scale involves three primary components: 1) scale-up of primary semiconductor operations; 2) vertical integration of secondary production operations to achieve cost minimization; and 3) replication of optimized production lines to achieve targeted factory capacity. In the thin-film sector of the photovoltaic industry, the first item has been the major stumbling block to achieving cost-competitiveness and profitability. This is a consequence of the relatively small capital investments made to date into manufacturing development and in the choices made regarding product design.

3.1 Manufacturing Scale-up and Replication

In the present approach, manufacturing scale-up can be rapidly achieved by employing continuous processing methodologies and by trading off economies-of-volume with economies-of-scale. In Table II, general processing parameters are presented for single continuous CIGS solar cell manufacturing lines with capacities of 2, 20, 200, and 2000 MW/yr.

Table II: Manufacturing parameters necessary to achieve various levels of production capacity for a single piece of deosition hardware..

Production Capacity (MWp/yr)	2	20	200	2000
Web Width (meters)	0.4	0.66	1.00[a]	2.50[a]
Yield / Uptime	0.70 / 0.34	0.80 / 0.68	0.85 / 0.85	0.90 / 0.85
Processing Speed (meter/hr)	29.4	63	138	500
Cell Efficiency (%)	10	11.5	13	14.5
Capital ($ Millions)	20 [b]	20	50	250
Ratio ($M / MW)	10	1	0.25	0.125

a. Web width is per side on a double-sided coating system
b. Includes startup costs.

Table III: Comparison of capital cost of CIGS solar cell manufacturing line employing different economies of scale and volume.

Factory Capacity (MW)	Line Capacity (MW)	20	200	2000
20	Method 1 [A]	$20M		
200	Method 1	$89M [c]	$100M [D]	
200	Method 2 [B]		$50M	
2000	Method 1	$400M	$447M	$500M [D]
2000	Method 2		$223M	$250M

a. Batch-continuous manufacturing
b. Fully continuous manufacturing
c. Learning curve factor of 0.787
d. Scaling factor of 0.70

In Table III, capital costs are presented for a range of total factory capacities that employ multiples of individual manufacturing lines. Method 1 embodies a batch-continuous manufacturing methodology that is employed in the production of monolithically integrated modules where there are multiple load and unload steps required to achieve cell interconnection using laser and mechanical scribing. Method 2 embodies a fully continuous cell manufacturing approach where there is only a single load and unload step required to manifest the semiconductor stack and a similar operation to manifest a finished cell (it is quite possible that cell deposition and finishing could eventually be linked together as well). It is understood that cells must be subsequently interconnected into modules.

A learning curve approach [5] is used to calculate the reduction in cost that would be achieved with replication. For example, a 20MW batch-continuous line that is replicated 10- and 100-times potentially achieves a 55% ($8.9M) and 80% ($4.0M) reduction in cost per line, respectively. If the same manufacturing methodology is scaled from 20 to 200 and 2000 MW/yr with a scaling factor of 0.7, the cost reductions are not as significant.

An alternate approach in quantifying the cost advantages of replication is by considering the standard volume cost reductions achieved when ordering custom designed industrial equipment. Volume purchase or blanket order agreements with equipment manufacturers typically attain cost reductions of 30 – 50 % from the single unit price. In this case, we would predict a per-line pricing of $10M -- $14M in volume. This estimate is supported by an alternate learning curve model with a learning rate at 90% (10% reduction in cost for each doubling of volume). The 90% estimate is appropriate for machinery which is 25% hand assembly and 75% machining [6], as we have with our current solar cell and panel production lines.

Based upon the processing parameters presented in Table II, we believe the 200 MW/yr continuous line will offer the best combination of economy of scale (relative to a 20 MW line) and economy of volume (10 lines required to achieve 2 GW/yr capacity). We estimate that such a line will have a capital cost of $50M, which is substantially less than either replicating or scaling a 20MW batch-continuous line. Additionally, replicating a 200MW line 10 times to achieve 2 GW results in the lowest capital cost for cell and module manufacturing hardware. (The cost of cell stringing and module packaging hardware is embedded in the fully-continuous line costs. Stringing and packaging is estimated to be $2.0M for 20 MW, which translates to either $0.4M per system if it is replicated 100 times, or $2.2M per system if it is scaled to 200MW and replicated 10 times).

3.2 Vertical Integration or the "Solar City" concept

In order to achieve the lowest manufacturing costs for not only the solar cell, but for the complete solar panel, we must evaluate vertical integration within each of the supply chains. Vertical integration along each supply chain is recommended where it is economically advantageous. Fig. 3 is an illustration of vertical integration within a CIGS solar cell factory.

In previous work, it has been determined that the manufacture of glass and aluminum for the solar panel packaging should be vertically integrated [3]. We have added the refinement of In and/or Ga, and the synthesis and formation of CIGS and other source materials to the production chain. Additionally, we propose that when manufacturing CIGS solar cells on a stainless steel substrate, the steel supply chain should be vertically integrated as well.

3.3 Vertical Integration of Stainless Steel

In considering material cost reductions, stainless steel is the largest component with a cost of $6.38/m^2 out of a total $12.29/m^2 for solar cell material. This makes it a significant opportunity for cost reductions. Additionally, the suppliers available to provide steel to current specifications are limited and are quoting long lead times, making it difficult to manage this part of the supply chain. Therefore we must consider what the cost and benefit is to bring this capability in house.

Figure 3: Vertically integrated, CIGS solar cell and module factory.

The stainless steel value chain is comprised of three major processes as shown in Fig. 4: melting/casting, hot rolling and cold finishing. Current pricing of 430 stainless steel finished to specifications is $2.85-5.00/lb. Current pricing of hot band steel that would be converted to specification through a cold rolling process is approximately $0.40 – 0.80 per pound. If we use the best pricing available, the cold finishing conversion cost is $2.40 per pound or 84% the cost of the stainless steel. Minimum capacity for melting/casting facility is approximately 0.5M ton per year – nearly 30 times the capacity needed to support 2 GW solar cell manufacturing, Based on this information, the most logical point for us to consider investing in steel processing capability is the cold finishing process.

Figure 4: Process flow for the conversion of raw material supply into finished sheet steel product.

The next factor to consider is the capital investment required for a cold finishing factory. If we look at historical data on similar facilities and project the cost into 2005, we can estimate an investment of $100M. This is also consistent with preliminary investigation of equipment costs. If this cost is amortized over 10 years, it would contribute $0.40/pound of cost of stainless steel. Add to this the actual material cost of $0.45/pound and an estimated conversion cost of $1.20/pound for a total cost of $2.05/pound to cold finish stainless steel in house. Compare this now with our best price for finished stainless steel of $2.85/pound and our conclusion is that it

is feasible to invest in this capability and it provides significant advantages by controlling this portion of the total material supply chain for reaching full-scale production.

4. OTHER CONSIDERATIONS

There are a variety of other considerations in the large-scale manufacture of a solar panel that is economically viable. These considerations span the technology and process domains and are driven out of the omipresent marketplace demand for electricity at competitive cost.

4.1 System-Level Return on Investment (ROI)

It has been generally proposed that the widespread adoption of solar electrical production will require an installed price of $1/W assuming a 5-year payback period. Current installed costs are approximately $5/W. We propose that a significant market exists within this range, receptive to prices even at levels near $3/W. This proposal is well-supported through the following observations:

1. The cost borne by the consumer is reduced by governmental programs which subsidize the installation price of and/or the sale price of electricity from solar installations.
2. A five year payback period for the installation may be too conservative considering that the design life of the installation is generally 30 years.
3. Electricity costs are steadily rising throughout the world. Consequently, payback from the installed array will increase throughout its lifetime.

Table IV: Payback at selected installation costs

Installation Cost ($/W)	Years to Payback	Present Value of Investment ($/W)
$5	16	$0.74
$4	12	$1.05
$3	9	$1.36
$2	6	$1.67
$1	3	$1.98

Assumptions: Retail kWh rates, 2% annual rate escalation, 6% cost of capital, 30y asset life, 33% installation cost subsidy

4.2 Worldwide Supply Constraints

Securing a steady supply of raw materials is a critical part of manufacutring both solar cells and panels at large scale. Any disruption in the timely and inexpensive flow of feedstock materials into the manufacturing process will result either in a production stoppage or a significant increase in the price of the feedstock materials. The primary feedstock materials are listed within table V along with the percentage of current (2004) global production that a 2GW factory would require.

Review of the primary feedstock materials shows that the largest procurement risk is present in the Indium (In) supply, followed by the Gallium (Ga) and Selenium (Se) supplies, respectively.

Indium is six times more abundant than silver within the environment, but its recovery is currently only economically viable as a byproduct of zinc mining. In recent years, demand has skyrocketed for indium as a component of Indium-Tin Oxide (ITO). These conductive coatings account for approximately 70% of total current world demand. The increased demand has caused a significant increase in the price of indium (currently $1100/kg), and therefore a challenge to production of solar cells with an attractive cost-basis.

Table V: Feedstock supply

Material	Utilization	Material Req'd @ 2GW (MT)	% of 2004 World Production
Molybdenum	75%	210.5	0.15%
Copper	75%	22.5	0.00%
Indium	75%	35.6	10.94%
Gallium	75%	3.6	5.15%
Selenium	75%	56.9	3.79%
ZnO	75%	11.4	0.00%
ZnO:Al	75%	57.2	0.00%
Al Grid	75%	38.6	0.00%
430SS Substrate	100%	15181.6	0.06%
Glass	100%	115684.1	0.35%
Aluminum Pkg	100%	28631.8	0.10%

Risk in the supply of indium can be mitigated through several techniques. First, the supply of indium can be secured at the source by partnering with a zinc smelter, preferably one currently without an indium recovery capability. The partnership would install and operate the required recovery equipment and execute the initial refinement of the indium into low-purity cast anodes. These anodes would then be brought in-house for final refinement and mechanical processing.

Secondly, the indium supply risk could be mitigated through supporting development of alternative coatings for the display industry. If lower cost and/or better performing coatings could be developed without indium, demand for the element could drop by as much as 70%.

Lastly, indium supply risk can be mitigated by making the most effective use of virgin indium possible. This can be accomplished through both the thinning of the absorber layer in the CIGS cell and through increased effectiveness of recycling techniques.

5.0 SUMMARY

Gigawatt-scale manufacturing of CIGS solar cells and modules will lead to significant cost reductions that could meet the $1/W cost target at the system level. Acceptable returns-on-investment, though, exists for intermediate system costs of up to $3/W. For the CIGS solar cell technology, the most significant cost hurdles that require attention are Indium and Gallium supply issues and substrate costs. Vertical integration of the manufacturing operations can mitigate these issues substantially.

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